

## A NOVEL TECHNIQUE FOR ACOUSTIC EMISSION MONITORING IN CIVIL STRUCTURES WITH GLOBAL FIBER OPTIC SENSORS.

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### Abstract

The application of Acoustic Emission (AE) - based damage detection is gaining interest in the field of civil structural health monitoring. Damage progress can be detected and located in real time and the recorded acoustic emissions hold information on the fracture process which produced them. One of the drawbacks for on-site application in large-scale concrete and masonry structures is the relatively high attenuation of the ultrasonic signal, which limits the detection range of the AE sensors. Consequently, a large number of point sensors are required to cover a certain area. To tackle this issue, a global damage detection system, based on acoustic emission detection with a polarization-modulated, single mode fiber optic sensor (FOS), has been developed. The sensing principle, data acquisition and analysis in time and frequency domain are presented. During experimental investigations, this acoustic emission fiber optic sensor is applied for the first time as a global sensor for detection of crack-induced acoustic emissions in a full-scale concrete beam. Damage progress is monitored during a cyclic four-point bending test and the AE activity, detected with the FOS, is related to the subsequent stages of damage progress in the concrete element. The results obtained with the AE-FOS are successfully linked to the mechanical behavior of the concrete beam and a qualitative correspondence is found with AE data obtained by a commercial system.

*Keywords: acoustic emission technique, fiber optic sensors, concrete, damage detection, experimental testing, signal analysis, structural health monitoring (SHM), ultrasonic, polarization*

### Research highlights:

- A novel technique for acoustic emission detection in large concrete structures, based on a polarization-modulated, single mode fiber optic sensor.
- The sensing principle, data acquisition and signal analysis are demonstrated by means of experimental testing of a concrete beam under cyclic four-point bending.
- A relation between results from the global fiber optic sensor and the mechanical behavior of the concrete beam is successfully obtained.

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## **1. Acoustic emission testing in large civil structures**

Structural health monitoring is an important tool to assess damage progress and remaining safety levels in existing structures and to support the design and evaluation of strengthening measures. For this purpose, the Acoustic Emission (AE) technique is an interesting option since damage progress can be detected and located in real time and the recorded acoustic emissions hold information on the fracture process which produced them. Acoustic Emissions (AE) are high-frequency transient elastic waves that are emitted within the material during local stress redistributions such as crack initiation and growth. These emissions are usually detected on the material's surface by means of piezoelectric (PZT) transducers, pre-amplified, filtered and amplified before being sent to the data logger.

It has been demonstrated that the AE technique is very useful for damage progress assessment and damage source characterization during laboratory testing on rock, concrete and masonry [1-10] and a restricted number of successful on-site campaigns has been reported [11-13]. One of the drawbacks when monitoring larger structures made from brittle, porous construction materials is the limited detection range of the sensors, caused by the high attenuation of ultrasonic waves. Therefore, a large amount of sensors is needed to cover a decent area and allow source location. To tackle this issue, a limited number of possibilities have been proposed, such as beamforming array techniques which rely on detection of Rayleigh waves and can be applied on simple, plate-like structures [13]. Wireless sensor networks were also proposed, but might pose problems of synchronization, power supply and cost in case of a large amount of sensors. It has been suggested that the use of micro-electro-mechanical-systems (MEMS) might largely reduce the sensor cost in the near future, although their signal-to-noise ratio is often worse compared to PZT sensors and they do not yet meet the requirements for AE detection [14, 15]. Both, MEMS and PZT sensors might suffer from electromagnetic interference.

In this study, a novel AE-detection system is presented for damage monitoring in large concrete and masonry structures, based on acoustic emission detection with a single mode fiber optic sensor (FOS) in a polarimetric setup. Optical fibers can be a valuable alternative to PZT sensors for AE detection in larger constructions, since one sensor can have an active length of several meters. FOS are insensitive to electromagnetic interference and can easily be embedded in other materials such as fiber reinforced polymers [16, 17] to produce "smart FRPs" or "self-sensing strengthening systems" for retrofitting of civil structures [18, 19].

Two main types of detection systems can be distinguished, being local and global FOS systems. Local sensors are positioned in a specific location and monitor the strains or acoustic emissions at that location. Examples are fiber Bragg gratings (FBG), which can be located at different points along an optical fiber to obtain data in several locations through multiplexing [20] or coiled sensors in which the optical fiber is wound to increase sensitivity [21]. Global sensors might operate as a fully distributed sensor network which can be interrogated at any point along the fiber length or integrate the response along the length of the fiber optic sensor and can thus cover a larger area [22, 23]. The disadvantage of global damage detection systems is the difficulty in accurately locating the damage once it has been detected. Therefore, hybrid local-global systems are applied to combine the damage detection possibilities and advantages of both systems. A global and local strain monitoring system was presented

by Jiang et al. [24] although they did not combine both in the same experimental setup. An interesting approach on a global, distributed crack sensor was presented by Bao et al. [25] who applied optical time domain reflectometry to measure the Rayleigh backscatter from fiber bends introduced by concrete cracks. By positioning the fiber in a zigzag pattern, they were able to detect crack location, orientation and opening. However, the crack pattern had to be very simple, with straight cracks which intersect the FOS twice and only crack openings larger than 0.5 mm could be reliably detected.

A number of techniques have been suggested for detection of acoustic emissions with fiber optic sensors. Good results have been obtained with interferometric setups which rely on detection of high-frequency phase modulations [23, 26] or with FBGs [22]. AE detection in concrete by means of fiber optic sensors has been investigated by Kageyama et al. [27] who applied coiled fiber sensors for detection of acoustic emissions in a concrete railway girder, based on the frequency shift of a light wave transmitted through a curved waveguide upon interaction with an ultrasonic wave. Although the developed sensors were point sensors, they could be multiplexed and showed high sensitivity. Chen et al. [28] applied a small fiber coupler-based AE sensor for damage detection in a concrete cube under compression. Obtained data could be fed into a commercial AE acquisition system. Schenato et al. [29] applied two different types of interferometric FOS to detect impact-induced acoustic emissions during experimental testing on a rock sample. Most studies apply the optical fiber as a point sensor, possibly multiplexed to obtain an array of point sensors which enables source location in case the ultrasonic wave attenuation is limited. Chen and Ansari [23] used a distributed fiber optic sensor in an interferometric setup for AE-detection. They introduced 'kinks' in the fiber to increase sensitivity at specific locations and allow linear AE source location in a steel beam, which has lower ultrasonic wave attenuation compared with concrete.

In this study, a global, integrating fiber optic sensor setup is applied for acoustic emission detection in civil structures. Single mode fiber optic sensors in a polarimetric setup are introduced for the first time for acoustic emission-based damage detection in concrete. The setup is comparable to the polarimetric sensors presented by Thursby et al. [22], although in our case, not the change in polarization state itself is monitored. When damage is initiated, the released elastic energy, in the form of acoustic emissions, causes a high-frequency pressure variation and perturbs the light in the sensing fiber. The sensing principle is further explained below. The proposed system distinguishes itself from other AE-FOS techniques by the following:

- The setup is straightforward and less complex compared to interferometers, which require a well-isolated, disturbance-free reference arm;
- The single mode (SM) fibers applied in this research are relatively cheap and do not require highly specialized equipment (hardware) for data acquisition;
- The FOS functions as a line-integrating sensor, integrating all the AE induced fluctuations along its length, which can be several meters, allowing to cover a larger area with a single sensor;
- The sensor does not contain FBG, coiled fibers or other individual point sensor components;

The major limitation of intensity-modulated FOS is that an intensity fluctuation in the output which is not related to a damage source, may cause erroneous results. Therefore, dedicated filtering is required and the repeatability of a single event detection is limited. A disadvantage of the line-integrating technique with a single FOS is that the location of the AE source along the fiber length cannot be determined unless a sensor grid or combination with multiplexed point sensors is made. This also means that two AE events, occurring within an extremely short time interval (dependent on the sampling rate), cannot be distinguished with the current setup. The setup also requires a physical connection between the concrete and FOS along the full sensing length to allow ultrasonic wave detection.

In the experimental study presented in this paper, a fiber optic sensor is applied for real-time AE-based damage detection in a concrete beam. Firstly, the principle of the novel AE detection setup, data acquisition and analysis will be explained. Secondly, the setup and results of the experimental test program will be presented and discussed. Damage progress in a concrete beam was monitored during a cyclic four-point bending test and acoustic emissions were detected with a fiber optic sensor and with piezoelectric transducers for comparison. The detected acoustic emissions will be related to the mechanical behavior of the concrete beam during subsequent stages of damage progress.

## **2. AE detection with polarization-modulated fiber optic sensors**

In initial work performed by Wevers and Rippert, intensity-modulated FOS were applied for damage detection in CFRP composite materials. Although sensitivity and signal/noise ratio were not satisfactory, detected AE transients could be compared with results obtained from AE monitoring systems [16, 30]. In the present work, an adapted version of this initial setup is applied. A polarimetric approach is used, which allows to control the detection range and thus to calibrate the sensitivity of the system at the start of the test. This polarimetric approach with single mode optical fibers was initially optimized for detection of ultrasonic surface waves in aircraft composites [31, 32]. In the presented research, the system was adapted to enable AE detection in brittle construction materials. To allow for the detection of AE waves in concrete (bulk waves), a high sampling rate was applied and optimization tests were performed to study the most favorable sensor location and contact medium between sensor and structure [33]. In the experimental work presented below, the polarization-modulated, single mode fiber optic sensor was applied for the first time in a successful, full-scale test on a concrete beam.

### **2.1 Detection setup**

The AE detection setup is schematically presented in [Figure 1](#). The polarimetric sensor configuration consists of following components:

- A laser (type Ando AQ-4141B) which sends light at 1310 nm wavelength is used as a stable light source;
- An isolator (Newport Isolator) is used to prevent light backscatter into the laser as this could destabilize the light source;
- A manual polarizer controller (Fiber Control Industries FPC-3) equipped with paddles is added for adjusting the initial, optimum polarization state;

- An embedded single mode optical fiber (type SMARTape, produced by SMARTEC SA.) is used as the sensing fiber.
- A polarizer is applied at the output of the FOS to isolate a particular polarization state.
- A photo diode transfers the light signal into a voltage signal.

The signal is subsequently amplified (UDT-1200A amplifier), filtered (Krohn-Hite model 3988 LP/HP dual channel filter, applied band pass: 500 Hz – 500 kHz) and digitized (8 channels National Instruments NI PXI-5105, of which only one channel is needed for the setup).

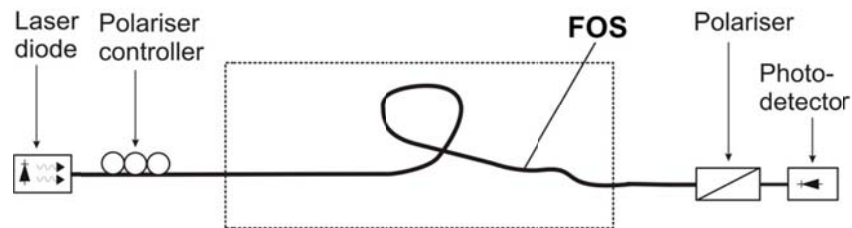


Fig 1: Polarimetric setup with single mode fiber optic sensor for AE transient detection.

## 2.2 Sensing principle

In an ideal single mode optical fiber, two polarized optical waves can propagate at the same velocity. External influences, such as ultrasonic waves, introduce birefringence leading to optical anisotropy. Consequently, the two polarized optical waves encounter different refractive indices and will propagate at different velocities, causing a phase shift. This birefringence thus causes variations in the polarization of the light at the output of the fiber. In addition to birefringence, the optical fiber will also show a degree of polarization dependent loss, which causes an additional intensity loss of a specific polarization state upon interaction with an acoustic wave. The change in degree of polarization dependent loss is assumed to be limited [34].

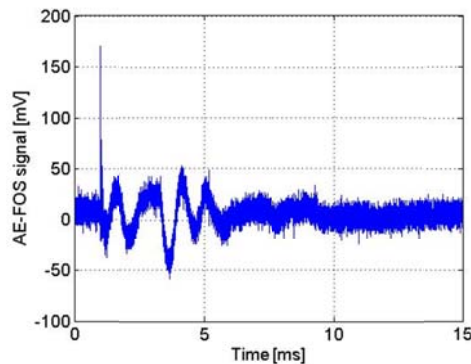
The polarizer at the fiber output isolates a particular polarization state. Not the change in polarization itself, but the change in the light intensity which varies due to the birefringence is monitored. Small perturbations of the light intensity indicate the interaction of AE waves with the light which propagates in the fiber optic sensor. The output of the polarizer is led to the photodetector, amplified, filtered and digitized.

The small perturbations in the light intensity, which are monitored as changes in the properties of the digitized signal, are buried in noise and require advanced filtering and signal processing to obtain information on the acoustic emission transients. The data within a sample buffer are only stored if a transient AE signal is detected within this sample range. In order to filter the transients from the noisy background signal and thus decide which signals need to be stored, a digital filtering algorithm is used during data acquisition.

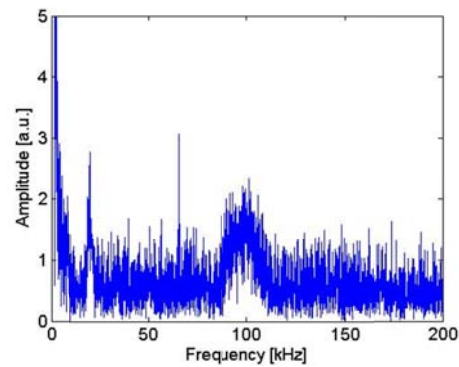
The filter algorithm is based on a segmentation of the discrete time signal and real-time signal processing in the frequency domain. Firstly, an initial noise level estimate is computed and the signal to noise ratio is improved by reconstruction of a new signal after spectral subtraction. The noise filter is continuously and automatically adapted throughout the test as the noise level might vary. Final detection of transients, which are identified as short-duration non-stationarities, is achieved by a constant false alarm rate power-law detector [35, 36]. A more detailed description of this algorithm can be found in Papy et al. [35]. Data acquisition and processing is performed in real-time using LabVIEW software. The software immediately depicts the cumulative AE event count, time of occurrence and the transient signal itself in the time domain. In addition, the detected transients are saved for further off-line analysis.

### 2.3 Calibration and signal analysis

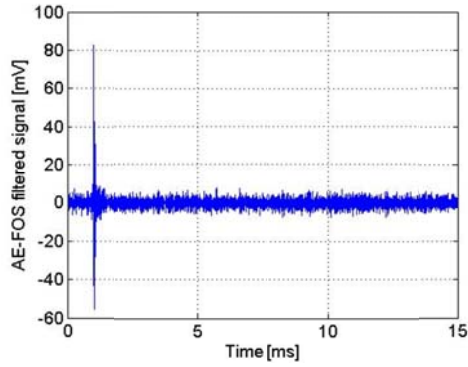
System calibration was performed by means of pencil lead breaks, similar to the calibration of a conventional AE system with PZT transducers [37]. The mechanical break of a pencil lead causes a signal comparable to an AE event. A sampling rate of 1 MHz was applied with a buffer size of 10\*1500 samples. **Figure 2a** presents an AE event induced by pencil lead break on the concrete beam at 1 cm from the FOS. Although the filter algorithm as described above is applied for the detection of AE transients, the algorithm functions only as a ‘detector’. After detection, the original signal within the sample buffer is stored. Thus the signal presented here is the original waveform, as stored at the moment of detection. The frequency spectrum of the signal is shown in **Figure 2b**.



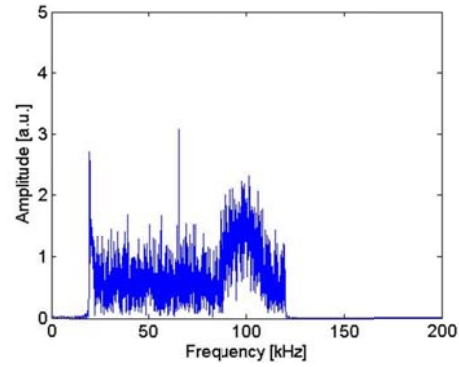
a)



b)



c)



d)

Fig 2: Waveform (a) and frequency spectrum (b) of an AE event induced by pencil lead break on a concrete beam and detected by means of a fiber optic sensor. Waveform (c) and frequency spectrum (d) of the filtered signal (high pass HP 20 kHz, low pass LP 120 kHz).

Off-line spectral analysis was performed by computing the Fourier transform in Matlab and applying a digital band pass filter between 20 - 120 kHz. Similar frequency ranges are commonly applied in case resonant PZT sensors are used for AE analysis in concrete. After exclusion of the lower frequency components (mechanical movement) and higher frequency components (system noise), a clear AE transient can be observed, see [Figure 2c and d](#). The fiber optic sensor acts as a broadband sensor, with frequencies of detected signals (in this case) ranging from 500 Hz to 500 kHz, depending on the analogue filtering stage and the sample frequency. As expected, highest response was observed for the lower frequencies. Mechanical movement can be excluded from the detected signals by increasing the value of the analogue high pass filter. During some of the tests, a noise source with a non-constant frequency content was observed, which we were not able to identify yet, but it is believed that the transient noise source is most probably caused by the laser. Therefore, further fine tuning of the setup is needed in order to enable application of the described monitoring system for long-term on-site AE detection.

### 3. Experimental program

#### 3.1 Test setup

The experimental setup is presented in [Figure 3](#). A concrete beam with dimensions 150 x 300 x 2500 mm<sup>3</sup> (height x width x length) was tested in a four-point bending test with a span of 2200 mm between supports and 500 mm between load points. Due to its restricted height (and thus restricted effective depth), the beam can be seen as a section from a concrete plate. Tensile and compressive reinforcement each consisted of 3 rebars with a diameter of 10 mm and compressive tests on cubes confirmed that a C25/30 concrete was applied.

Acoustic emissions were detected with a fiber optic sensor with an active fiber length of 2 meters. For easy handling and installation of the optical fiber, a SMARTape fiber optic sensor was applied. The sensor consists of a single mode optical fiber embedded in a glass fiber reinforced polymer (GFRP) tape with a width of 12 mm. The SMARTape was glued on the side of the concrete beam with a 2-component methyl methacrylate glue. This glue provides good acoustic coupling, but might require additional consideration when applied for long-term testing in an outside environment due to limited resistance against humidity. The SMARTape was fixed at 10 cm from the underside of the beam, thus at the upper 1/3 of the beam height. This position was firstly chosen to avoid that large cracks, originating from the tension zone at the underside of the beam, would break the fiber optic sensor at an early stage during the test. Secondly, this position of the FOS enables to check if active crack tips, located at a certain distance from the optical fiber, can be detected.

In addition to the FOS system, acoustic emissions were also monitored with four PZT transducers with 150 kHz resonance frequency connected to a Vallen Amsy-5 AE acquisition system (detected frequency range 120-450 kHz). The AE sensors were placed above but on the same side as the FOS and at 40 cm apart. When a calibration pulse was send from the sensors, it was noticed that each AE sensor was in range of its direct neighbor. The maximum detection distance of a pencil lead break by the AE sensors was 50 cm.

A semi-cyclic loading scheme was applied in a force-controlled setup with a loading velocity of 0.2 kN/sec. The force was cycled between 1 kN (base load to avoid unloading and too large deformations during the test) and 'X' kN, in which the value of 'X' was started at 4 kN and after each three cycles, it was increased with 4 kN. A schematic loading stage consisting of a sequence of 3 cycles is indicated in [Figure 4](#).

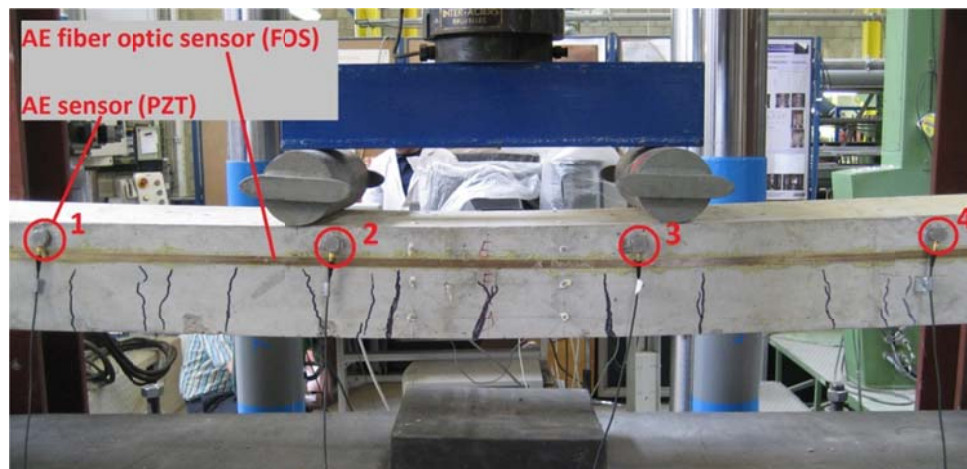


Fig 3: Four-point bending test setup and sensor locations



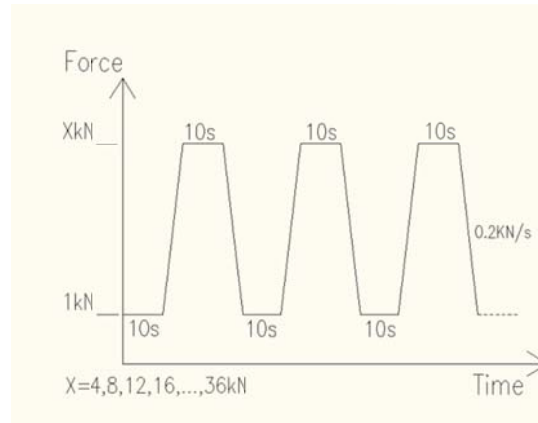


Fig 4: Loading scheme applied during cyclic four-punt bending test on concrete beam

This loading scheme was chosen firstly to allow observation of the Kaiser effect in three subsequent cycles with equal maximum force and secondly to observe failure from rebar yielding and/or concrete crushing upon stress increase. Aim of the test is to check the effectiveness of the FOS system for detecting crack initiation and growth in concrete, even if crack tips are located at a distance from the sensor, and to correlate the results of both AE systems.

### 3.2 Results

The force-deflection evolution measured during the test is presented in [Figure 5](#). The deflection of the concrete beam is recorded as the stroke of the hydraulic press, which is a slight underestimation of the midspan deflection. The graph is divided into 4 intervals, which will be referred in the discussion below. At the end of the first interval, the first visible cracks are observed in the concrete beam in the midspan area between the loading points, which is the zone with a maximum and constant moment. In the second interval, additional cracks are formed. Interval three does not show much damage increase, while from the start of interval 4, the width of the cracks in the midspan area increases significantly and failure of the beam is initiated through yielding of the reinforcement.

This typical behavior of a reinforced concrete beam under four-point bending can be observed from an analysis of the acoustic emission data obtained by the piezoelectric transducers. [Figure 6](#) presents the located AE events within each of the four time intervals in a cumulative manner. Location data are only available in 2D, along the beam's lateral axis due to the 2D sensor setup. The Y-axis indicates the cumulative amplitude of all events located in a zone of 2 cm wide. The zone width of 2 cm corresponds to the average location error for this setup. It can be observed that cracks first appear between the two loading points. In interval 2, these cracks grow while additional cracks are formed to the left and right of the loading points. All cracks grow steadily in interval 3, while the AE energy release in interval four is mostly located in the midspan area where rebar yielding occurs. This is in accordance with the visual observations made during the test and with the above discussion of the results presented in [Figure 5](#). It

has to be noticed that the occurrence of cracks increases the heterogeneity of the concrete, which could cause relevant changes in AE wave velocity and attenuation in different directions. Therefore, the location error could increase and a large number of AE sources would not be located towards the end of the test.

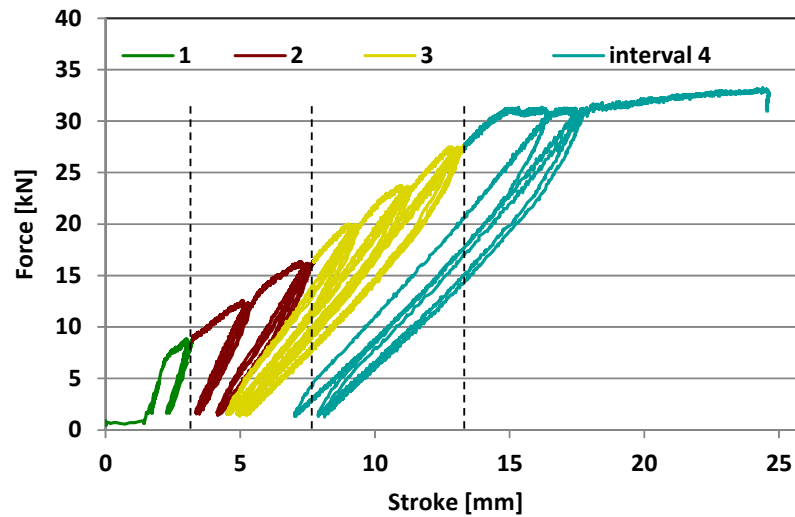


Fig 5: Force-deflection evolution recorded during four-point bending test on concrete beam

Further, it has to be remarked that a location analysis such as presented here can only be performed for concrete elements with limited size since the AE sensors need to be closely spaced. In a previous test program on masonry arches, the AE sensors were not closely spaced and damage location was only possible if cracks occurred in the vicinity of the sensors, while the FOS on the other hand was able to monitor the complete mechanical behavior of the arches and detect the moment at which the collapse mechanism was formed [38]. In the further discussion, it will be shown that the damage which was detected by the closely spaced AE point sensor network was also picked up by the single fiber optic sensor although, as discussed before, damage location is not possible with the chosen FOS-setup.

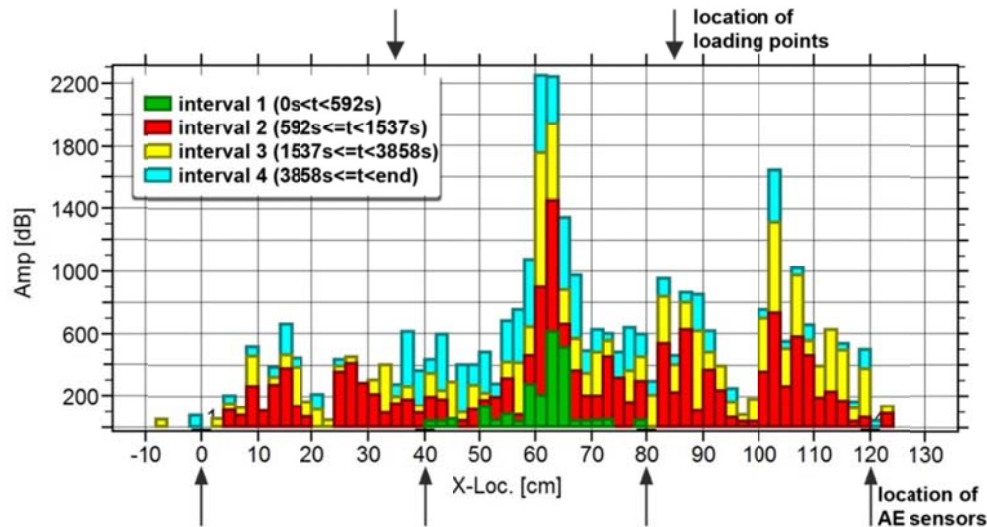


Fig 6: AE location graph (obtained from Vallen software): cumulative amplitude distributions of AE events recorded during subsequent time intervals at locations along the length of the beam (bar width is 2 cm).

Figure 7 compares the cumulative number of AE events detected by the piezoelectric sensors and by the fiber optic sensor. All AE hits detected by the four PZT transducers are added together in one cumulative graph. If an AE source is picked up by two or more PZT sensors (multiple hits), it is represented only once (one event) in the graph. A threshold of 55 dB is applied for event counting. Again, the four intervals are indicated. From Figure 7, it can be noticed that the PZT sensors detect acoustic emissions throughout the test, with a larger number of detected AE events each time the stress level is increased. During the first cycles of the test, the subsequent two loading cycles after stress increase produce an insignificant number of acoustic emissions, while the loading cycles which incorporate a load increase exceeding the previously obtained maximum load level produce a large number of acoustic emissions. This 'memory' of the material for the previously obtained maximum load levels is known as the Kaiser effect [6]. At higher load levels, acoustic emissions are recorded during each stress cycle, even if the previously applied maximum load level is not exceeded. This is called Felicity effect and is evidence of substantial structural defects [6]. It was observed that also the unloading of the concrete beam produces acoustic emissions (friction in existing cracks and crack closure), even though the beam was never fully unloaded as a base load of 1 kN was applied.

A slightly different pattern is observed when analyzing the cumulative AE graph obtained with the fiber optic sensor. In general, fewer AE events are detected. In interval 1 and 2, during crack initiation, AE detection by the fiber optic sensor is similar to the results obtained from the PZT sensors. It was observed that the FOS detected the crack initiation very well, even if crack tips were located at a certain distance, 5-10 cm, below the fiber optic sensor. In interval 3, during which the existing cracks grow slightly, very few AE hits are detected by the FOS and the sensor seems less sensitive to the detection of

repeated opening and closing of the existing cracks. From the onset of interval 4, the number of detected fiber optic acoustic emission events increases significantly and the imminent failure of the beam is detected. It can be concluded that the results of the fiber optic sensor provide a very good representation of the overall behavior of the structural component.

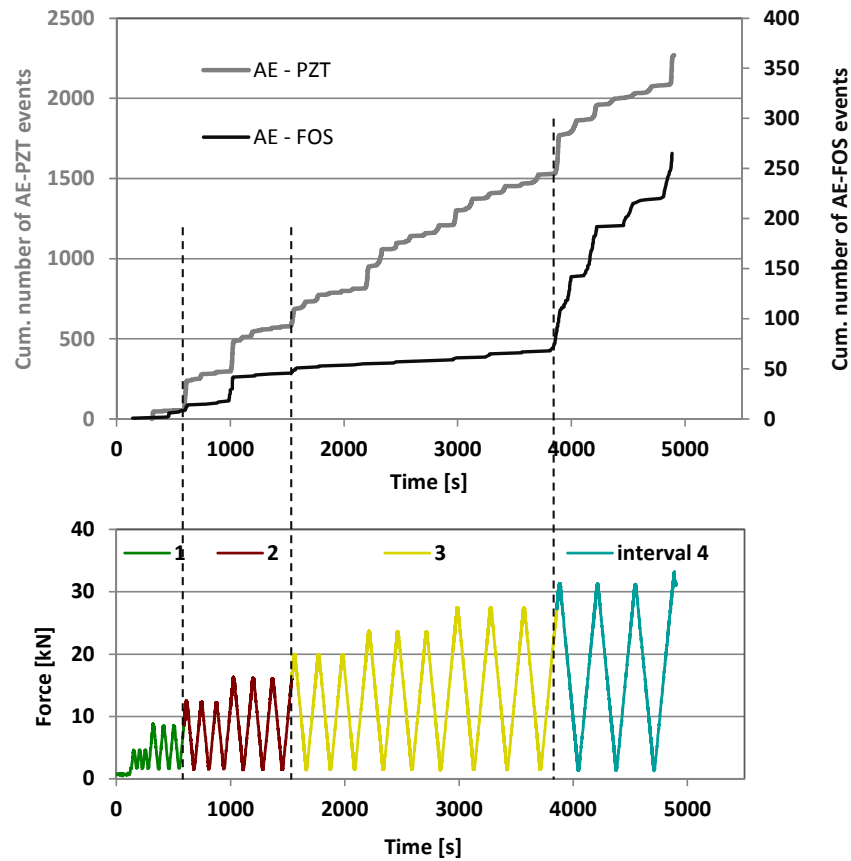


Fig 7: Comparison between cumulative number of AE events recorded with four piezoelectric transducers and with a fiber optic sensor. The lower graph presents the evolution of the applied load.

Since the AE-PZT sensors and the AE-FOS sensor differ in sensor position, sensitivity, sampling rate, frequency response and frequency band filter, they do not detect the exact same AE events nor the same total amount of AE events. However it was observed during testing and data analysis that some of the acoustic events with large energy content were detected simultaneously by both sensor types. During calibration testing, when only one event is simulated by means of a pencil lead break, it is certain that both detections are caused by the same AE event. But as expected, the waveforms are not equal due to a difference in propagation path of the AE wave and a difference in sensor type (point sensor versus line integrating sensor), sampling frequency, frequency response and sample window size of both AE detection systems. In the discussion below, it is assumed that two AE detections, arriving simultaneously at the different AE systems, originate from the same source.

Figure 8 presents the AE events detected by means of the commercial PZT sensors and the fiber optic sensor during the first loading stages of the cyclic four-point bending test. The symbol size is related to the maximum amplitude of each AE event. A very good agreement is observed between the results of both AE systems. One of the high-energy acoustic emission events which was detected at the same moment by both systems is indicated in Figure 8 and the respective waveforms are presented in Figures 9a-c. It is assumed that both signals originate from the same AE source.

The AE-PZT signal, Figure 9a, has a high signal to noise ratio and shows many reflections (the transient signals which are present in the second half of the sample window). The window size is limited to 0.35 milliseconds due to the software setup of the commercial system. The AE-OFS signal has lower signal to noise ratio but a much larger window size, up to 6 milliseconds, Figure 9b. A very long AE signal is detected, which is due to reflections but also a consequence of the line integrating principle. All fluctuations along the FOS length are integrated. The AE propagation path is shortest perpendicular to the fiber, so this causes the initial detection, while wave components with a longer propagation path will be more attenuated and are picked up in the tail of the signal. Figure 9c presents a magnification of the signal presented in Figure 9b on the same timescale as the AE-PZT signal. The difference in sample rate (1 MHz for the FOS system versus 10 MHz for the PZT system), which is related to the software and hardware restrictions of the current systems, does not allow for a quantitative comparison of the AE data of both AE detection methods. However, comparison of obtained data shows a good correlation between the results of the AE point sensor network and the AE fiber optic sensor, qualitatively as well as in terms of arrival time and signal strength.

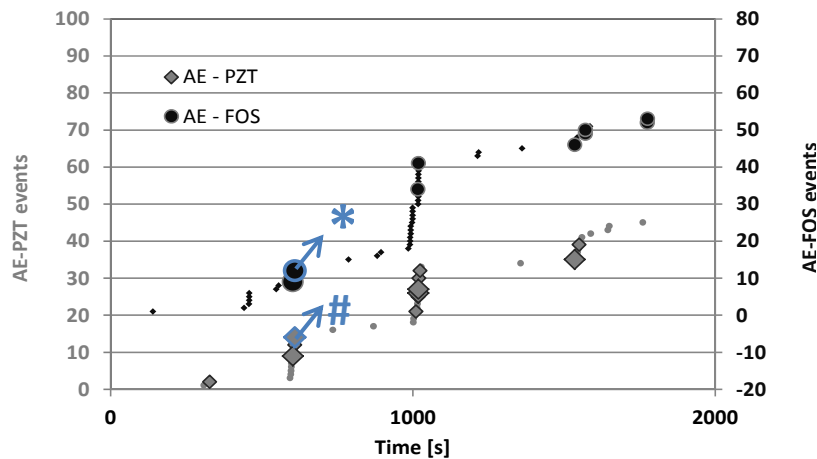


Fig. 8: AE events at the first loading stages of the test, with indication of an event which was detected by both systems.

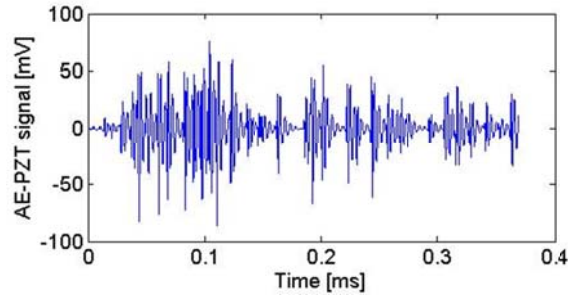


Fig. 9a. AE-PZT event as indicated in Figure 8 (#).

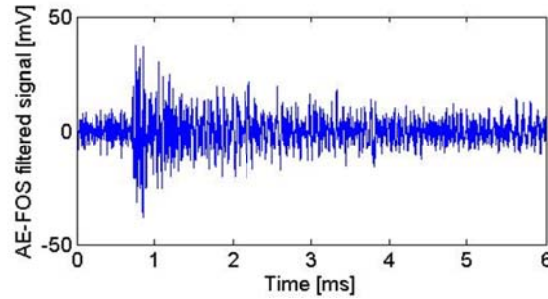


Fig 9b. AE-FOS event as indicated in Figure 8 (\*). Note the different time axis scale.

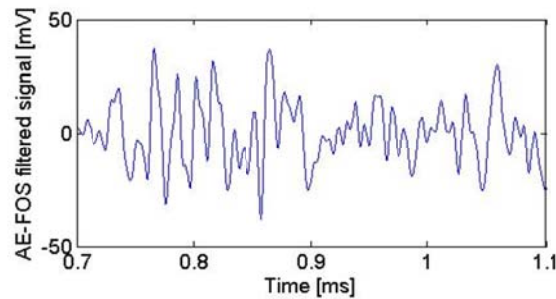


Fig 9c. Magnification of AE-FOS event presented in Figure 9b.

#### 4. Conclusions

A novel technique for acoustic emission detection with a polarization-modulated, line-integrating fiber optic sensor was presented. This system allows for AE detection in large structures. The detection setup, data acquisition and filtering process were briefly discussed. The developed system showed simplicity and robustness as it is intended for on-site application on civil structures.

The effectiveness of the fiber optic acoustic emission sensor was proven in a cyclic four-point bending test on a concrete beam. Acoustic emissions caused by crack initiation and growth were detected with the novel fiber optic sensor and with a commercial AE system with piezoelectric transducers. Results indicated that damage induced acoustic emissions in concrete can be detected with the presented FOS

setup even if the crack tip is located at a certain distance from the optical fiber. Good agreement was found between the AE data obtained by means of PZT sensors and the developed AE-FOS. Moreover, it was concluded that the AE-FOS data were related to the observed structural behavior. Although sensitivity of the fiber optic sensor to AE transients is less compared with piezoelectric transducers, the crack initiation, overall mechanical behavior and imminent failure of the concrete beam were successfully detected by the novel AE-FOS system.

The challenge at this point is a further development of the signal filtering and post-processing as to distinguish more clearly between different event sources and an adaptation of the system hardware (laser) to facilitate on-site measurements. It was shown in this paper that results obtained by the AE-FOS system can be linked to the mechanical behavior of a concrete beam under four-point bending and can thus potentially be applied to predict damage progress levels during on-site application. For this purpose, a combination of the current setup with additional systems for measuring different physical quantities (humidity, temperature, strains) is to be developed.

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## References

- [1] Aggelis D.G., Soulioti D.V., Sapouridis N., Barkoula N.M., Paipetis A.S., Matikas I.E. Acoustic emission characterization of the fracture process in fibre reinforced concrete. *Construction and Building Materials* 2011; 25(11):4126-4131.
- [2] Tomor A.K., Verstrynge E. A joint fatigue–creep deterioration model for masonry with acoustic emission based damage assessment. *Construction and Building Materials* 2013; 43:575-588.
- [3] Verstrynge E., Schueremans L., Van Gemert D., Wevers M. Monitoring and predicting masonry's creep failure with the acoustic emission technique. *NDT & E International* 2009; 42(6):518-523.
- [4] Anzani A., Binda L., Carpinteri A., Lacidogna G., Manuello A. Evaluation of the repair on multiple leaf stone masonry by acoustic emission. *Materials and Structures* 2008; 41(6):1169-1189.
- [5] Grosse C.U., Finck F. Quantitative evaluation of fracture processes in concrete using signal-based acoustic emission techniques. *Cement and Concrete Composites* 2006; 28(4):330-336.
- [6] Grosse C.U., Ohtsu M., eds. *Acoustic emission testing - basics for research - applications in civil engineering*. Springer. (2008).
- [7] Ganne P., Vervoort A., Wevers M. Quantification of pre-peak brittle damage: Correlation between acoustic emission and observed micro-fracturing. *International Journal of Rock Mechanics and Mining Sciences* 2007; 44(5):720-729.
- [8] Colombo I.S., Main I.G., Forde M.C. Assessing damage of reinforced concrete beam using "b-value" analysis of acoustic emission signals. *Journal of Materials in Civil Engineering* 2003; 15(3):280-286.

- [9] Eberhardt E., Stead D., Stimpson B. Quantifying progressive pre-peak brittle fracture damage in rock during uniaxial compression. *International Journal of Rock Mechanics and Mining Sciences* 1999; 36(3):361-380.
- [10] Shiotani T. Evaluation of long-term stability for rock slope by means of acoustic emission technique. *Ndt & E International* 2006; 39(3):217-228.
- [11] Carpinteri A., Invernizzi S., Lacidogna G. AE structural assessment of a 17th century masonry vault, in 5th International Seminar on Structural Analysis of Historical Constructions, Lourenco P.B., et al., Editors: New Delhi. 2006.
- [12] De Santis S., Tomor A.K. Laboratory and field studies on the use of acoustic emission for masonry bridges. *Ndt & E International* 2013; 55:64-74.
- [13] McLaskey G.C., Glaser S.D., Grosse C.U. Beamforming array techniques for acoustic emission monitoring of large concrete structures. *Journal of Sound and Vibration* 2010; 329(12):2384-2394.
- [14] Krüger M., Grosse C.U., Kurz J.H. Report on Wireless Sensor Networks using MEMS for Acoustic Emission Analysis including other Monitoring - Tasks Report D5.5 of project "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives", co-funded by the European Commission under FP6. 2007.
- [15] Ozevin D., Greve D.W., Oppenheim I.J., Pessiki S.P. Resonant capacitive MEMS acoustic emission transducers. *Smart Materials & Structures* 2006; 15(6):1863-1871.
- [16] Wevers M., Rippert L., Papy J.M., Van Huffel S. Processing of transient signals from damage in CFRP composite materials monitored with embedded intensity-modulated fiber optic sensors. *Ndt & E International* 2006; 39(3):229-235.
- [17] Zhou G., Sim L.M. Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors - review. *Smart Materials & Structures* 2002; 11(6):925-939.
- [18] Bastianini F., Corradi M., Borri A., di Tommaso A. Retrofit and monitoring of an historical building using "Smart" CFRP with embedded fibre optic Brillouin sensors. *Construction and Building Materials* 2005; 19(7):525-535.
- [19] Wang C., Cheng L. Use of fiber Bragg grating sensors for monitoring concrete structures with prestressed near-surface mounted carbon fiber-reinforced polymer strips. *Journal of Intelligent Material Systems and Structures* 2013.
- [20] Lee B. Review of the present status of optical fiber sensors. *Optical Fiber Technology* 2003; 9(2):57-79.
- [21] Hayano T., Matsuo T., Cho H., Takemoto M. Optical fiber system for AE monitoring of high temperature damage of stainless steel tubing. *J. Acoustic Emission* 2006; 24:67-75.
- [22] Thursby G., Sorazu B., Betz D., Staszewski W., Culshaw B. The use of fibre optic sensors for damage detection and location in structural materials. *Advances in Experimental Mechanics* 2004; 1-2:191-196.
- [23] Chen Z., Ansari F. Fiber optic acoustic emission distributed crack sensor for large structures. *Journal of Structural Control* 2000; 7(1):119-129.
- [24] Jiang G.L., Dawood M., Peters K., Rizkalla S. Global and Local Fiber Optic Sensors for Health Monitoring of Civil Engineering Infrastructure Retrofit with FRP Materials. *Structural Health Monitoring-an International Journal* 2010; 9(4):309-322.
- [25] Bao T.F., Wang J.L., Yao Y.A. A fiber optic sensor for detecting and monitoring cracks in concrete structures. *Science China-Technological Sciences* 2010; 53(11):3045-3050.
- [26] Ansari F. Fiber optic health monitoring of civil structures using long gage and acoustic sensors. *Smart Materials & Structures* 2005; 14(3):S1-S7.



- [27] Kageyama K., Murayama H., Ohsawa I., Kanai M., Nagata K., Machijima Y., et al. Acoustic emission monitoring of a reinforced concrete structure by applying new fiber-optic sensors. *Smart Materials & Structures* 2005; 14(3):S52-S59.
- [28] Chen R., Burns J.M., Bradshaw T., Cole P., Jarman P., Theobald R., et al. Acoustic Emission detection using a novel fibre optic sensor. *Acoustic Emission Testing* 2006; 13-14:99-104.
- [29] Schenato L., Palmieri L., Gruca G., Iannuzzi D., Marcato G., Pasuto A., et al. Fiber optic sensors for precursory acoustic signals detection in rockfall events. *Journal of the European Optical Society-Rapid Publications* 2012; 7.
- [30] Rippert L., Wevers M., Van Huffel S. Optical and acoustic damage detection in laminated CFRP composite materials. *Composites Science and Technology* 2000; 60(14):2713-2724.
- [31] Pfeiffer H., Wevers M. Aircraft integrated structural health assessment - structural health monitoring and its implication within the European project AISHA *Journal of non-Destructive Testing and Evaluation International* 2008; art.nr. ID: 6966.
- [32] Pitropakis I., Pfeiffer H., Wevers M. The use of a polarimetric fibre sensor to detect impact damage in aircraft composites, in *International Conference on Emerging Technologies in Non-Destructive Testing, ETNDT 2011: Ioannina, Greece. 2011.*
- [33] Verstrynge E., Wevers M. Initial results on acoustic emission detection in masonry with optical fibre sensors in *30th European Conference on Acoustic Emission Testing / 7th International Conference on Acoustic Emission, NDT.net, Editor: Granada. 2012.*
- [34] Wevers M., Van Huffel S., Vandenplas S., Papy J.-M. Acoustic emission monitoring using a polarimetric single mode optical fibre sensor. *International Journal for Materials and Structural Integrity* 2007; 1(1/2/3):148-160.
- [35] Papy J.M., Van Huffel S., Rippert L., Wevers M. On-line detection method for transient waves applied to continuous health monitoring of carbon fiber reinforced polymer composites with embedded optical fibers. *Smart Structures and Materials 2003: Modeling, Signal Processing, and Control* 2003; 5049:718-731.
- [36] Wang Z., Willett P.K. All-purpose and plug-in power-law detectors for transient signals. *Ieee Transactions on Signal Processing* 2001; 49(11):2454-2466.
- [37] EN 13477-2 Non-destructive testing. Acoustic emission. Equipment characterisation. Verification of operating characteristic. 2010.
- [38] Verstrynge E. A novel technique for AE-based damage monitoring in masonry arches with optical fibre sensors, in *Proceedings of the 7th International Conference on Arch Bridges, Radic J., Kuster M., Savor Z., Editors: Trogir, Croatia. 2013. p. 663-672.*